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Measurement of Short-Term Frequency Stability of Controlled Oscillators

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A method for measuring the frequency of a controlled oscillator as a function of time is described. Sometimes it is necessary to detect and measure small but fast frequency changes. This method can also be used to measure frequency-hopping radio transmitters or radar pulses. In these cases suggested measurement tools, e.g. spectrum analyzers or frequency counters cannot be used.

The performance of the system depends mostly on the multimeter, whose accuracy, noise and speed set the limits for the measurements. So far we have been able to measure frequency changes of 5 Hz with sampling speed of 100 000 s^{-1}. The observed uncertainty is less than 2 Hz. With some further noise reduction better results are expected.

I. INTRODUCTION

Crystal oscillators provide nowadays a very accurate timebase. There are, however, some factors that may cause instability of the frequency. These are, e.g. temperature, humidity or pressure changes, acceleration or changes in their external load [1]. On the other hand, the frequency of the oscillator can also be changed intentionally, for example in voltage or oven controlled crystal oscillators (VCXO, OCXO)[2].

Sometimes it is necessary to measure fast frequency changes, caused by either external factors or intentional tuning, for example, in pulsed or chirped radars or in frequency hopping radios. Radar pulses are typically very short, so a predefined amount of measurements must be done during short time period. Frequency deviation during pulse may be hard to detect.

In chirped radars, the pulse is longer but has a frequency shift. In frequency hopping radios, frequency is changed typically in several millisecond intervals, but the change in frequency is significant and therefore easier to measure than radar pulses.

The primary target of this research is, however, to measure the frequency of controlled oscillators during the adjustment, when a frequency counter is too slow and domain-type analyzers are too inaccurate. This setup is also used to measure nonlinearities of controlled oscillators [3]. The goal of this research was to reach an uncertainty of less than 5 Hz and a measurement rate better than 20 000 s^{-1}.

Frequency counters provide accurate results, but can not be used for fast measurements, because a short gate time decreases accuracy too much. The data transfer rate of the communications bus may also be a factor that limits the measurement rate. A modulation domain analyzer was also used, but when measurement time was shortened, accuracy dropped substantially.

Characterization of frequency stability is discussed more in [4] and [5], for example.

II. MEASUREMENT SETUP

Block diagram of the setup is presented in Figure 1. It consists of a power splitter, coaxial delay line, mixer, attenuator, low-pass filter, DC-amplifier and a $8\frac{1}{2}$-digit multimeter. The output of the oscillator under test is connected to the splitter, whose first output goes straight to the RF-input of a mixer. The second signal from the splitter is delayed and connected to the LO-port. Because of the delay, there's a phase difference between two signals in mixer's inputs.

When the frequencies in the RF-port and LO-port are equal, a DC-voltage is present in the output of the mixer, proportional to the phase difference ϕ. In an idealized case, output voltage $v(t)$ of the mixer is

$$v(t) = A_1 \sin(\omega t) \cdot A_2 \sin(\omega t + \phi) = \frac{A_1 A_2}{2}(\cos(\phi) - \cos(2\omega t + \phi)). \quad (1)$$

The length of the delay line was tuned to generate a phase difference of 90° with measured frequency. With this arrangement output voltage is 0 V, as stated in Equation 1, and the response of the measurement system is linear as a function of frequency.

High-frequency components are filtered using a low-pass filter. An attenuator is used between mixer and filter to ensure proper impedance matching. The filtered signal, which now consists only of DC-voltage, is amplified using a low-noise operational amplifier, whose gain is 100. The amplifier is battery powered to reduce unintentional noise.

The DC-voltage is measured using a fast bus-controlled multimeter (digital voltmeter, DVM). The speed and accuracy of the multimeter defines also the sampling speed and accuracy of the frequency measurement. The uncertainty of the voltage measurement is defined by calibrating the multimeter using the same integration time and measurement range as in the actual frequency measurement.

The multimeter used in this setup was Agilent 3458A, which was calibrated using Keithley model 263 calibrator. The multimeter was connected to a PC via

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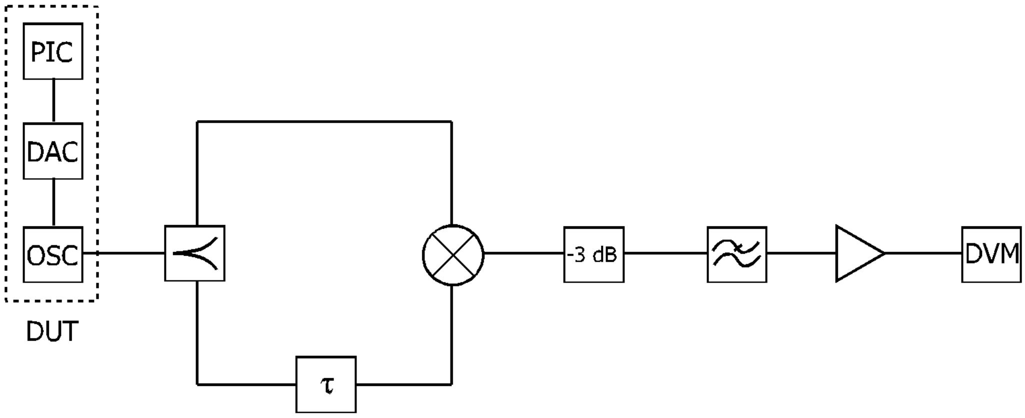

FIG. 1: Block diagram of the setup. PIC microcontroller drives the digital to analog-converter (DAC), which supplies the control voltage for the voltage controlled oscillator (VCXO), marked in the figure as OSC. Signal from the oscillator is split, and splitter's first output goes straight to the mixer. The second signal from the splitter is delayed and connected to the LO-port of the mixer. Mixer's output signal is attenuated and filtered using low-pass filter. The remaining DC-component is amplified and voltage is measured using digital voltmeter (DVM).

GPIB-bus. LabView-software was used to control the multimeter and to save the results.

The input impedance of the multimeter is very high, over 10 GΩ. Because a DC amplifier is used, the input impendace can be reduced to minimize noise. In this setup, 1 kΩ precision resistor was connected to the input terminals of the DVM.

A precise controller for voltage controlled oscillator (VCXO) was also needed. It is used to supply wanted waveform for desired frequency modulation, but it is also needed in defining the frequency scale. We used Microchip's PIC microcontroller, which is connected to 16 bit digital to analog-converter (DAC). DAC has parallel data bus and current output. It drives a low-noise operational amplifier, which was used as current to voltage converter.

PIC was programmed to produce a waveform that creates a linear frequency sweep (sweep measured with the modulation domain analyzer can be seen in Figure 2). Program also allowed us to measure a number of stable frequencies, which were used in defining the measurement scale of the setup.

Similar frequency measurement methods based on the phase detector and phase shifter have been presented before [6, 7], but an important difference is, that in this setup no reference oscillator is used. Measured frequency is compared to itself, and possible frequency fluctuations of the reference oscillator do not affect the results. Therefore the absolute frequency is not known, but only the differential frequency change, which in this research was the focus.

III. RESULTS

The output voltage of the setup was measured as a function of frequency. Eight different control voltages,

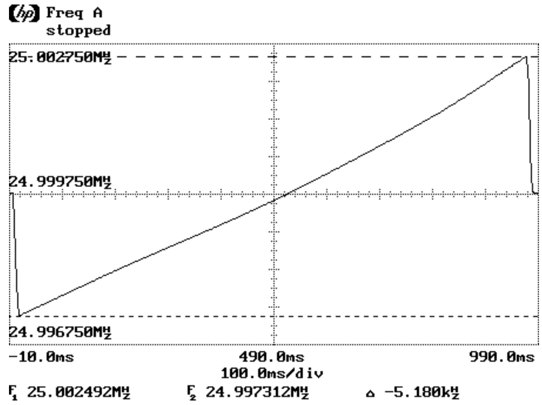

FIG. 2: Frequency of the VCXO in function of time measured with Agilent 53310A modulation domain analyzer. Center frequency ic ca. 25 MHz, frequency change is 5,18 kHz and sweep duration is 1 second.

which covered the whole tuning range of the measured VCXO, were used. VCXO output requencies were measured with frequency counter, and output voltages of the setup were measured respectively. Results are presented in figure 4; sensitivity is 0,139 mV/Hz.

Since the length of the delay line is tuned to generate a phase difference of about 90°, the output voltage is near 0 V and the response is linear.

The multimeter used in the setup was calibrated using the same settings as in frequency measurements. To achieve best possible measurement rate, averaging was not used, and the integration time was set to 0. The measurement range was 1 volt, and single precision was used to transfer results to the computer. With single precision, each result is transferred using two bytes.

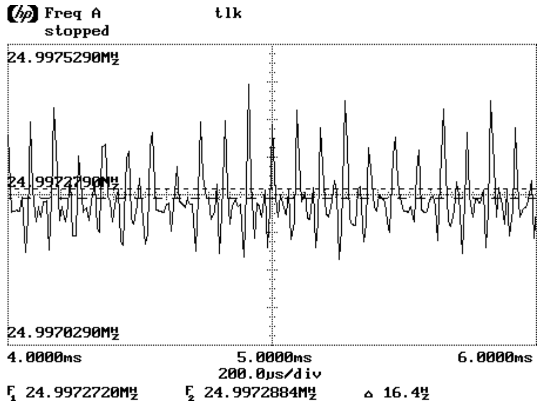

FIG. 3: The requency deviation of tested oscillator measured using modulation domain analyzer. Frequency deviation of 300 Hz shown in the figure is not plausible.

The multimeter was calibrated using Keithley model 263 calibrator. Triaxial cable was used to connect calibrator to the multimeter. Calibration was done with 0 V, 1 V and -1 V voltages. Observed voltage measurement uncertainty was 0,22 mV.

Using double precision in data transfer (4 bytes/result) did not provide lower uncertainty. Because averaging was not used, uncertainty was considerably higher than normally. The noise of the DC-amplifier was also measured, but it's contribution to the overall uncertainty was minimal.

When integration time is set to 0, the measurement speed of Agilent 3458A is 100 000 s^{-1}. Results are stored temporarily in DVM's internal memory, and transferred to the PC when the measurement is finished. The capacity of the internal memory is ca. 75 000 results, and if memory runs out, measurement rate drops dramatically. Therefore, the longest usable measurement time is about 0,75 seconds.

An example of the measurement done using described setup can be seen in Figure 5. The measured worst case frequency fluctuation between two samples was 5 Hz. The measured oscillator was Axtal Axis 10, with nominal frequency of 25 MHz. The measurement duration was 500 μs and it was done during a frequency sweep, shown in Figure 2.

When a modulation domain analyzer was used to measure same oscillator using more accurate time scale, frequency deviation of over 300 Hz was observed (Figure 3). With a shorter measurement time deviation increased. This kind of result is not plausible, and our method can be considered better in such precise measurements.

IV. CONCLUSIONS

A simple and cheap setup for measuring small differential frequency changes was presented. Measurement rate is 100 000 s^{-1} and the observed uncertainty is 1,6 Hz. The described setup is very flexible, it can be modified for even more precise frequency measurements by using longer delay line. A drawback is that the linear frequency range decreases. On the other hand, with shorter delay useful frequency range can be very wide.

Our results show, that using this kind of setup, fast frequency changes can be measured with greater measurement rate than with frequency counter, and far more accurately than with modulation domain analyzer.

In near future, better results may be obtained if noise is further reduced. It may be done by improving either the voltage supply used to control the VCXO or the DC-amplifier.

Since the performance of the setup depens mostly on the performance of the multimeter, high-quality instruments must be used. Calibration is also necessary, because normal calibrations are done using longer integration times.

The described setup can also be used in long-term stability measurements. Software, that controls the multimeter, provides possibility to measure output voltage of the setup with longer intervals (e.g. 1 second . . . 10 minutes)

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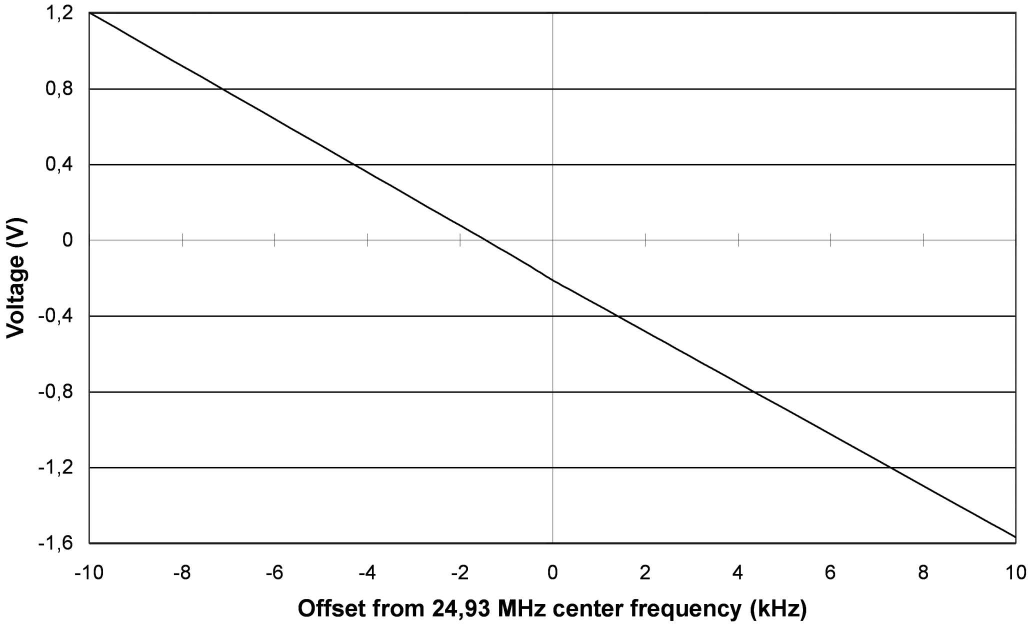

FIG. 4: Measured frequency scale. Microcontroller and digital to analog converter were used to feed stable control voltage to the VCXO. A number of stable frequencies were measured using frequency counter and output voltages of the setup were measured respectively. The response of the setup is linear in the whole measurement region, and sensitivity is 0,139 mV/Hz.

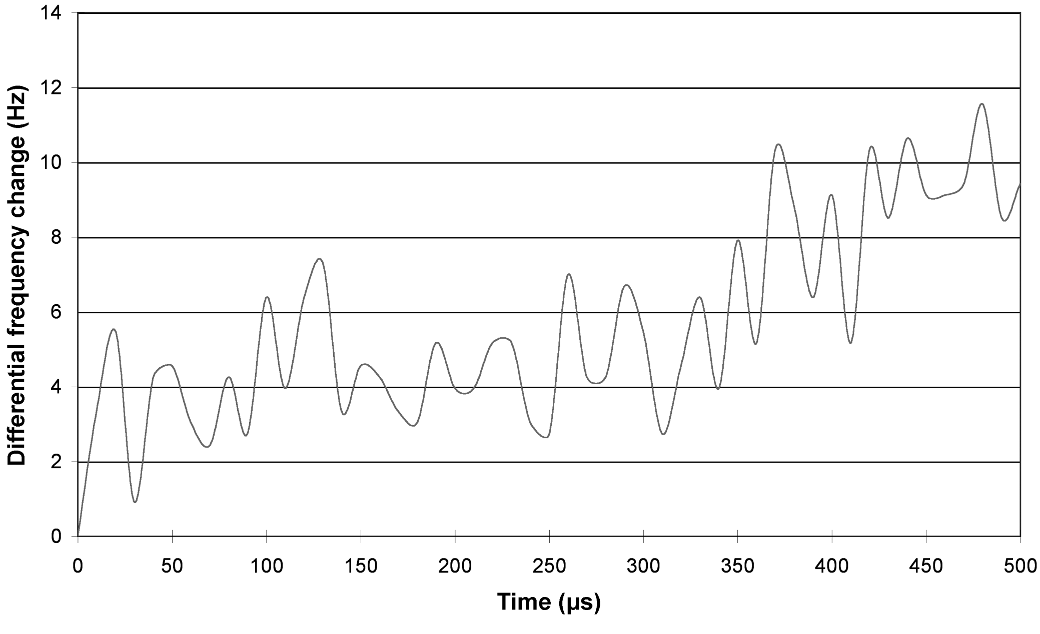

FIG. 5: The differential frequency fluctuation of the measured oscillator. Measurement time is 500 μs, measurement rate is 100 000 s^{-1} and measured frequency deviation is less than 5 Hz. Frequency is rising because the time period shown in this figure is part of longer frequency sweep (see Figure 2), where frequency changes over 5 kHz.